

**IN THE UNITED STATES PATENT AND TRADEMARK OFFICE**

Applicant:	Xing SU et al.	Conf. No. :	9817
Application No.:	10/697,682	Group Art Unit:	1654
Filing Date:	October 29, 2003	Examiner:	Julie Ha
Title:	METHODS AND DEVICE FOR ANALYTE CHARACTERIZATION		

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**APPEAL BRIEF**

Mail Stop: Appeal Brief – Patents  
Commissioner for Patents  
P.O. Box 1450  
Alexandria, VA 22313-1450

Dear Sir:

As required under § 41.37(a), this brief is filed within two months of the Notice of Appeal filed concurrently herewith and is in furtherance of said Notice of Appeal.

The fees required under § 41.20(b)(2) are dealt with in the accompanying TRANSMITTAL OF APPEAL BRIEF.

This brief contains items under the following headings as required by 37 C.F.R. § 41.37 and M.P.E.P. § 1205.2:

- I. Real Party In Interest
- II. Related Appeals and Interferences
- III. Status of Claims
- IV. Status of Amendments
- V. Summary of Claimed Subject Matter
- VI. Grounds of Rejection to be Reviewed on Appeal
- VII. Argument
- VIII. Claims Appendix

- IX. Evidence Appendix
- X. Related Proceedings Appendix

#### I. REAL PARTY IN INTEREST

The real party in interest for this appeal is Intel Corporation

#### II. RELATED APPEALS AND INTERFERENCES

The appeal co-pending U.S. Patent Application Serial No. 10/138,157 may directly affect or be directly affected by or have a bearing on the Board's decision in this appeal.

#### III. STATUS OF CLAIMS

##### A. Current Status of Claims

1. Claims pending: 1-8, 10-16, and 32-35
2. Claims canceled: 9, and 17-31
3. Claims withdrawn from consideration but not canceled: None
4. Claims allowed: None
5. Claims rejected: 1-8, 10-16, and 23-35

##### B. Claims On Appeal

The claims on appeal are claims 1-8, 10-16, and 23-35

#### IV. STATUS OF AMENDMENTS

Applicants filed an After Final Amendment on August 10, 2009. The amendment was entered with the Advisory Action of August 25, 2009.

## V. SUMMARY OF CLAIMED SUBJECT MATTER

1. (Previously presented) A method comprising:

a) placing a plurality of labeled proteins, polypeptides or peptides {Page 4, ¶ [0030], Lines 1-5} in a plurality of chambers, such that different chambers contain a different type of labeled amino acid { Page 5, ¶ [0036], Lines 1-2};

b) passing the labeled proteins, polypeptides or peptides through one or more nanopores { Page 6, ¶ [0036], Lines 4-6}, an inner surface of the nanopores coated with a semiconductor material { Page 25, ¶ [0097], Lines 4-8};

c) detecting labeled amino acid residues in the labeled proteins, polypeptides or peptides { Page 5, ¶ [0032], Lines 2-4};

d) compiling an amino acid distance map for each type of labeled amino acid { Page 6, ¶ [0036], Lines 7-8}; and

e) identifying the protein based on the distance maps { Page 6, ¶ [0036], Lines 8-9}.

## VI. GROUNDS OF REJECTION TO BE REVIEWED ON APPEAL

Whether claims 1, 4-5, 7-8, 10-14, 16 and 35 are unpatentable under 35 U.S.C. 102(b) as being anticipated by Chan (US Patent No. 6,210,896)?

Whether claims 1, 4-5, 7-8, 10-14, 16 and 35 are unpatentable under 35 U.S.C. 102(e) as being anticipated by Chan (US Patent No. 6,355,420)?

Whether claims 1, 3-5, 7-8, 10-14, 16 and 35 are unpatentable under 35 U.S.C. 103(a) as being unpatentable over Chan (US Patent 6,210,896)?

Whether claims 2, 6, 15 and 32-34 are unpatentable under 35 U.S.C. 103(a) as being obvious over Chan (US Patent No. 6,210,896) as applied to claims 1, 3-5, 7-8, 10-14, 16 and 35 in view of Thompson et al (US Patent No. 5,324,637)?

Whether claims 2, 6, 15 and 34-35 are unpatentable under 35 U.S.C. 112, first paragraph for not providing enablement for producing one or more labeled proteins, polypeptides or peptides encoded by the template nucleic acid?

## VII. ARGUMENT

### A. Rejection under 35 U.S.C. 102(b) as being anticipated by Chan (US Patent No. 6,210,896) should be overturned

#### 1. Claims 1, 4-5, 7-8, 10-14, 16 and 35

a. Neither Chan '896 nor Chan '420 teach "passing the labeled proteins, polypeptides or peptides through one or more nanopores, an inner surface of the nanopores coated with a semiconductor material"

i. The instant application teaches distinct semiconductor and metal-based sensor layer embodiments.

In the Advisory Action, the Examiner acknowledges that "the reference (Chan '896) explicitly teaches **metal** composition coating the nanopores." (Advisory Action, third paragraph under Maintained Rejections, line 7)(Emphasis added). The Examiner also acknowledges "Chan '420 explicitly teaches that the 'membrane can also be produced such that both faces of the membrane are covered with thin **metal** films to produce a nanodisk electrode ensemble." (*Id.* at paragraph six, lines 2-3)(Emphasis added). To maintain the anticipation rejections, the Examiner alleges "[a]s indicated in the office action, the instant specification has been utilized to define what a 'semiconductor material' is, and the instant specification discloses that 'the sensor layers may comprise semiconductor material including, but not limited to, silicon, silicon dioxide, silicon nitride, germanium [sic], gallium [sic] arsenide [sic], and/or metal-based compositions such as metals or metal oxides.'" (*Id.*, third paragraph, lines 7-11)(Emphasis added).

While the Examiner has correctly quoted from paragraph [0067] of the instant application (paragraph [0078] of the published application), the Examiner's interpretation of paragraph [0067] is incorrect. The Examiner has interpreted of

paragraph [0067] of the specification to define “semiconductor” as including “metal-based compositions such as metals or metal oxides.” The quoted sentence, however, describes various sensor layer compositions, it does not define “semiconductor.” As discussed in the response filed February 18, 2009 (page 7, lines 21-23) and emphasized with the bolding below, paragraph [0067] of the specification teaches multiple embodiments comprising different sensor layers including: (1) sensor layers comprising a semiconductor **and/or** (2) sensor layers comprising metals or metal oxides. “The **sensor layers** may comprise semiconductor materials including, but not limited to, silicon, silicon dioxide, silicon nitride, germanium, gallium arsenide, **and/or** metal-based compositions such as metals or metal oxides.” (Paragraph [0067]) The claims on appeals are drawn to the first embodiment, sensor layers comprising semiconductor materials.

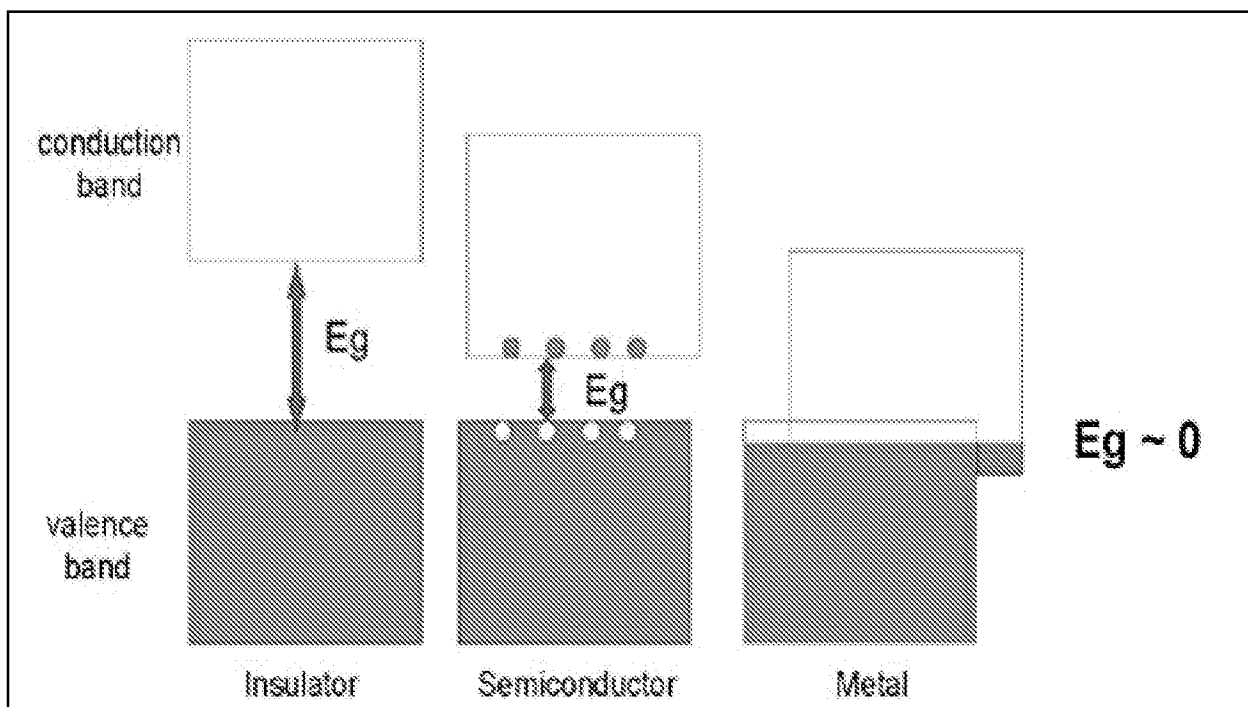
Both Chan ‘896 and Chan ‘420 admittedly teach sensor layers comprising metals, not semiconductors. For at least this reason, neither Chan ‘896 and Chan ‘420 anticipates claims 1, 4-5, 7-8, 10-14, 16 and 35.

ii. A metal is not a semiconductor

Semiconductors and metals are fundamentally different. As discussed in the response filed February 18, 2009, semiconductors and insulators have a band gap between the valence and conduction bands, with semiconductors having smaller band gaps relative to insulators. See the attached Wikipedia entry on Semiconductors originally filed in the Response dated February 18, 2009 and illustration below. Metals, in contrast do not have a band gap. That is, the conduction band and the valence band overlap in a metal. This lack of a band gap is the fundamental difference between a metal and a semiconductor or insulator. Indeed, it is the lack of a band gap which makes metals good conductors of electricity. The large band gap of insulators, in contrast, is responsible for the inability for insulators to conduct electricity. One of ordinary skill in the art would recognize that metal covered sensor layer is not the same as a semiconductor covered sensor layer. Although claims are given their broadest reasonable interpretation during examination “[t]he protocol of giving claims their

broadest reasonable interpretation during examination does not include giving claims a legally incorrect interpretation. *In re Skvorecz*, 2008-1221, slip op. at 8. (Fed. Cir. 2009). Equating metals and semiconductors is legally incorrect. Chan '896 and Chan '420 simply do not anticipate claims 1, 4-5, 7-8, 10-14, 16 and 35.

**Schematic band diagrams for an insulator, a semiconductor, and a metal.**



- B. Rejection under 35 U.S.C. 102(e) as being anticipated by Chan (US Patent No. 6,355,420) should be overturned
  - 1. Claims 1, 4-5, 7-8, 10-14, 16 and 35
    - a. (Same as above)
- C. Rejection under 35 U.S.C. 103(a) as being unpatentable over Chan (US Patent 6,210,896) should be overturned
  - 1. Claims 1, 3-5, 7-8, 10-14, 16 and 35
    - a. No combination of Chan '896, Chan '420, and Thompson teach or suggest "passing the labeled proteins, polypeptides

or peptides through one or more nanopores, an inner surface of the nanopores coated with a semiconductor material”

As discussed above, neither Chan ‘896 nor Chan ‘420 teach “passing the labeled proteins, polypeptides or peptides through one or more nanopores, an inner surface of the nanopores **coated with a semiconductor material.**” Thompson was merely cited for teaching “a method for coupling transcription and translation from DNA, wherein RNA is transcribed from DNA and RNA translates into protein.” (Final Office Action, page 15, lines 10-12). Indeed, Thompson does not even teach the use of nanopore sensors. Thus, even if Chan ‘896 or Chan ‘420 were combined with Thompson, the resulting method would not include “passing the labeled proteins, polypeptides or peptides through one or more nanopores, an inner surface of the nanopores coated with a semiconductor material” as recited in independent claim1. Thus, no combination of Chan ‘896, Chan ‘420 and/or Thompson would have rendered claims 1-8, 10-16 and 32-35 obvious to one of ordinary skill in the art at the time of the invention.

- D. Rejection under 35 U.S.C. 103(a) as being obvious over Chan (US Patent No. 6,210,896) as applied to claims 1, 3-5, 7-8, 10-14, 16 and 35 in view of Thompson et al (US Patent No. 5,324,637) should be overturned
  - 1. Claims 1, 3-5, 7-8, 10-14, 16 and 35
    - a. (Same as above)
- E. Rejection under 35 U.S.C. 112, first paragraph for not providing enablement for producing one or more labeled proteins, polypeptides or peptides encoded by the template nucleic acid should be overturned
  - 1. Claims 2, 6, 15 and 34-35
    - a. The specification provides enablement for one of ordinary skill in the art to produce one or more labeled proteins, polypeptides or peptides encoded by the template nucleic acid.

In the Advisory Action, the Examiner acknowledges that the specification is “enabling for producing labeled nucleic acid from the template nucleic acid.” (Advisory

Action, page 3, second paragraph, lines 2-3). The Examiner alleges, however, “no art provide guidance as how to produce labeled proteins, polypeptides or peptides from a template nucleic acid, since **not all template nucleic acids** would encode **the same** labeled proteins, polypeptides or peptides.” (Id. at fourth paragraph, lines 3-5)(Emphasis added).

The Examiner mischaracterizes the claimed invention. None of the claims recite any language that requires **all** template nucleic acids to encode **the same** labeled proteins, polypeptides or peptides. Claim 2 merely calls for a template nucleic acid and producing “one or more labeled proteins, polypeptides or peptides encoded by **the** template nucleic acid.” That is, the recited method only calls for those labeled proteins, polypeptides or peptides encoded **by a given template** nucleic acid. One of ordinary skill in the art at the time of the invention desiring to produce particular labeled proteins, polypeptides or peptides need only to select the appropriate template nucleic acid.

Further, paragraph [0036] of the specification explicitly teaches that “Labeled proteins encoded by the nucleic acid template may be produced by *in vitro* translation or by linked transcription/translation.” That is, the specification explicitly teaches at least two methods, (1) *in vitro* translation and (2) by linked transcription/translation, for “producing one or more labeled proteins, polypeptides or peptides encoded by the template nucleic acid.” Thus, the specification is enabled for the recited method – “producing the one or more labeled proteins, polypeptides or peptides encoded by **the** template nucleic acid.”

In view of the above amendment, applicant believes the pending application is in condition for allowance. The Director is authorized to charge any fees necessary and/or credit any overpayments to Deposit Account No. 03-3975, referencing Docket No. 043395-0378252.

Respectfully submitted,

Dated: November 6, 2009

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## VIII. Claims Appendix

1. (Previously presented) A method comprising:

a) placing a plurality of labeled proteins, polypeptides or peptides in a plurality of chambers, such that different chambers contain a different type of labeled amino acid;

b) passing the labeled proteins, polypeptides or peptides through one or more nanopores, an inner surface of the nanopores coated with a semiconductor material;

c) detecting labeled amino acid residues in the labeled proteins, polypeptides or peptides;

d) compiling an amino acid distance map for each type of labeled amino acid;  
and

e) identifying the protein based on the distance maps.

2. (Currently amended) The method of claim 1, further comprising:

a) placing a template nucleic acid into each chamber; and

b) producing the one or more labeled proteins, polypeptides or peptides encoded by the template nucleic acid.

3. (Original) The method of claim 1, further comprising: a) obtaining one or more proteins, polypeptides or peptides from a biological sample; and b) labeling the proteins, polypeptides or peptides post-translationally.

4. (Original) The method of claim 1, wherein the protein, polypeptide or peptide is identified by comparing the distance maps with a library of amino acid distance maps.

5. (Original) The method of claim 1, wherein the protein, polypeptide or peptide is identified by comparing the distance maps with the sequences of known proteins.

6. (Original) The method of claim 2, wherein each chamber is operably coupled to a different set of nanopores.

7. (Original) The method of claim 1, wherein each nanopore is operably coupled to a detector.

8. (Original) The method of claim 1, wherein only one labeled protein, polypeptide or peptide passes through a nanopore at a time.

9. (Cancelled)

10. (Original) The method of claim 1, wherein the length of time between passage of a first labeled amino acid through the nanopore and passage of a second labeled amino acid through the nanopore corresponds to the distance along the labeled protein, polypeptide or peptide between the first and second amino acids.

11. (Original) The method of claim 1, wherein the labels are selected from the group consisting of luminescent labels, fluorescent labels, phosphorescent labels, chemiluminescent labels, conductive labels, nuclear magnetic resonance labels, mass spectroscopy labels, electron spin resonance labels, electron paramagnetic resonance labels and Raman labels.

12. (Original) The method of claim 1, wherein at least one end of the labeled protein, polypeptide or peptide is attached to an identifiable label.

13. (Original) The method of claim 1, wherein said labeled amino acids are detected with a photodetector.

14. (Original) The method of claim 1, wherein said labeled amino acids are detected with an electrical detector.

15. (Original) The method of claim 2, further comprising analyzing a multiplicity of labeled proteins, polypeptides or peptides from each chamber.

16. (Original) The method of claim 1, further comprising determining at least a partial sequence of the protein, polypeptide or peptide based on the distance maps.

17-31. (Cancelled)

32. (Previously Presented) The method of claim 2, wherein the one or more labeled proteins, polypeptides or peptides encoded by the template nucleic acid is produced by *in vitro* translation or by linked transcription/translation.

33. (Previously Presented) The method of claim 32, wherein *in vitro* translation is performed with mRNA templates.

34. (Currently amended) The method of claim 32, wherein *in vitro* translation carried out in cell systems of rabbit reticulocyte lysates, wheat germ extracts, or *E. coli* extracts.

35. (Previously Presented) The method of claim 1, wherein the distance map shows distances in a sub-nanometer scale.

IX. Evidence Appendix

Appellants rely on the following evidence pursuant to §§1.130, 1.131, or 1.132 of this title:

The following Wikipedia entry on Semiconductors originally filed in the Response dated February 18, 2009.

# Semiconductor

From Wikipedia, the free encyclopedia

A **semiconductor** is a solid material that has electrical conductivity between those of a conductor and an insulator; it can vary over that wide range either permanently or dynamically.<sup>[1]</sup>

Semiconductors are essential in electronic technology. Semiconductor devices, electronic components made of semiconductor materials, are essential in modern consumer electronics, including computers, mobile phones, and digital audio players. Silicon is used to create most semiconductors commercially. Dozens of other materials are used.

## Contents

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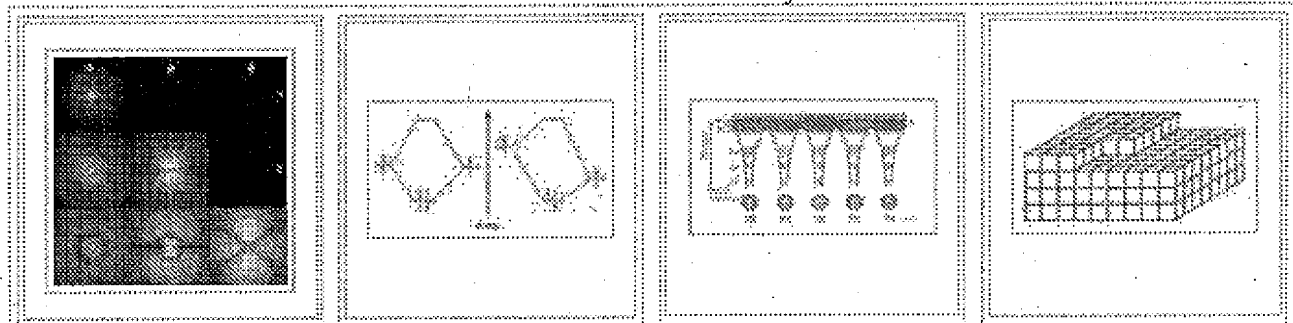
## Explaining semiconductor energy bands

There are three popular ways to describe the electronic structure of a crystal.

- Band structure

*For more details on this topic, see [Electronic band structure](#).*

atoms - crystal - vacuum

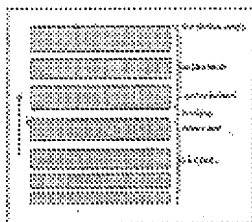


In a single H-atom an electron resides in well known orbits. Note that the orbits are called s,p,d in order of increasing circular current.

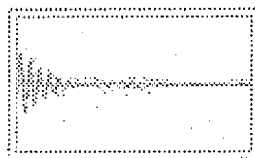
Putting two atoms together leads to delocalized orbits across two atoms, yielding a covalent bond. Due to the Pauli exclusion principle, every state can contain only one electron.

This can be continued with more atoms. Note: This picture shows a metal, not an actual semiconductor.

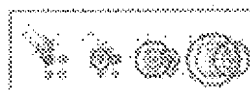
Continuing to add creates a crystal, which may then be cut into a tape and fused together at the ends to allow circular currents.



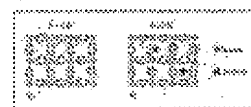
Integrating over the k axis gives the bands of a semiconductor showing a full valence band and an empty conduction band. Generally stopping at the vacuum level is undesirable, because some people want to calculate: photoemission, inverse photoemission



After the band structure is determined states can be combined to generate wave packets. As this is analogous to wave packages in free space, the results are similar.



An alternative description, which does not really appreciate the strong Coulomb interaction, shoots free electrons into the crystal and looks at the scattering.



A third alternative description uses strongly localized unpaired electrons in chemical bonds, which looks almost like a Mott insulator.

### Bragg reflection in a diffuse lattice

A second way starts with free electrons waves. When fading in an electrostatic potential due to the cores, due to Bragg reflection some waves are reflected and cannot penetrate the bulk, that is a band gap opens. In this description it is not clear, while the number of electrons fills up exactly all states below the gap.

### Energy level splitting due to spin state Pauli exclusion

A third description starts with two atoms. The split states form a covalent bond where two electrons with spin up and spin down are mostly in between the two atoms. Adding more atoms now is supposed to lead not to splitting, but to more bonds. This is the way silicon is typically drawn. The band gap is now formed by lifting one electron from the lower electron level into the upper level. This level is known to

be anti-bonding, but bulk silicon has not been seen to lose atoms as easy as electrons are wandering through it. Also this model is most unsuitable to explain how in graded hetero-junction the band gap can vary smoothly.

## Energy bands and electrical conduction

Like in other solids, the electrons in semiconductors can have energies only within certain bands (ie. ranges of levels of energy) between the energy of the ground state, corresponding to electrons tightly bound to the atomic nuclei of the material, and the free electron energy, which is the energy required for an electron to escape entirely from the material. The energy bands each correspond to a large number of discrete quantum states of the electrons, and most of the states with low energy (closer to the nucleus) are full, up to a particular band called the *valence band*. Semiconductors and insulators are distinguished from metals because the valence band in the semiconductor materials is very nearly full under usual operating conditions, thus causing more electrons to be available in the conduction band.

The ease with which electrons in a semiconductor can be excited from the valence band to the conduction band depends on the band gap between the bands, and it is the size of this energy bandgap that serves as an arbitrary dividing line (roughly 4 eV) between semiconductors and insulators.

In the picture of covalent bonds, an electron moves by hopping to a neighboring bond. Because of the Pauli exclusion principle it has to be lifted into the higher anti-bonding state of that bond. In the picture of delocalized states, for example in one dimension that is in a wire, for every energy there is a state with electrons flowing in one direction and one state for the electrons flowing in the other. For a net current to flow some more states for one direction than for the other direction have to be occupied and for this energy is needed. For a metal this can be a very small energy in the semiconductor the next higher states lie above the band gap. Often this is stated as: full bands do not contribute to the electrical conductivity. However, as the temperature of a semiconductor rises above absolute zero, there is more energy in the semiconductor to spend on lattice vibration and — more importantly for us — on lifting some electrons into an energy states of the *conduction band*, which is the band immediately above the valence band. The current-carrying electrons in the conduction band are known as "free electrons", although they are often simply called "electrons" if context allows this usage to be clear.

Electrons excited to the conduction band also leave behind electron holes, or unoccupied states in the valence band. Both the conduction band electrons and the valence band holes contribute to electrical conductivity. The holes themselves don't actually move, but a neighboring electron can move to fill the hole, leaving a hole at the place it has just come from, and in this way the holes appear to move, and the holes behave as if they were actual positively charged particles.

One covalent bond between neighboring atoms in the solid is ten times stronger than the binding of the single electron to the atom, so freeing the electron does not imply destruction of the crystal structure.

## Holes: electron absence as a charge carrier

The notion of holes, which was introduced for semiconductors, can also be applied to metals, where the Fermi level lies *within* the conduction band. With most metals the Hall effect reveals electrons to be the charge carriers, but some metals have a mostly filled conduction band, and the Hall effect reveals positive charge carriers, which are not the ion-cores, but holes. Contrast this to some conductors like solutions of salts, or plasma. In the case of a metal, only a small amount of energy is needed for the

electrons to find other unoccupied states to move into, and hence for current to flow. Sometimes even in this case it may be said that a hole was left behind, to explain why the electron does not fall back to lower energies: It cannot find a hole. In the end in both materials electron-phonon scattering and defects are the dominant causes for resistance.

The energy distribution of the electrons determines which of the states are filled and which are empty. This distribution is described by Fermi-Dirac statistics. The distribution is characterized by the temperature of the electrons, and the *Fermi energy* or *Fermi level*. Under absolute zero conditions the Fermi energy can be thought of as the energy up to which available electron states are occupied. At higher temperatures, the Fermi energy is the energy at which the probability of a state being occupied has fallen to 0.5.

The dependence of the electron energy distribution on temperature also explains why the conductivity of a semiconductor has a strong temperature dependency, as a semiconductor operating at lower temperatures will have fewer available free electrons and holes able to do the work.

### Energy-momentum dispersion

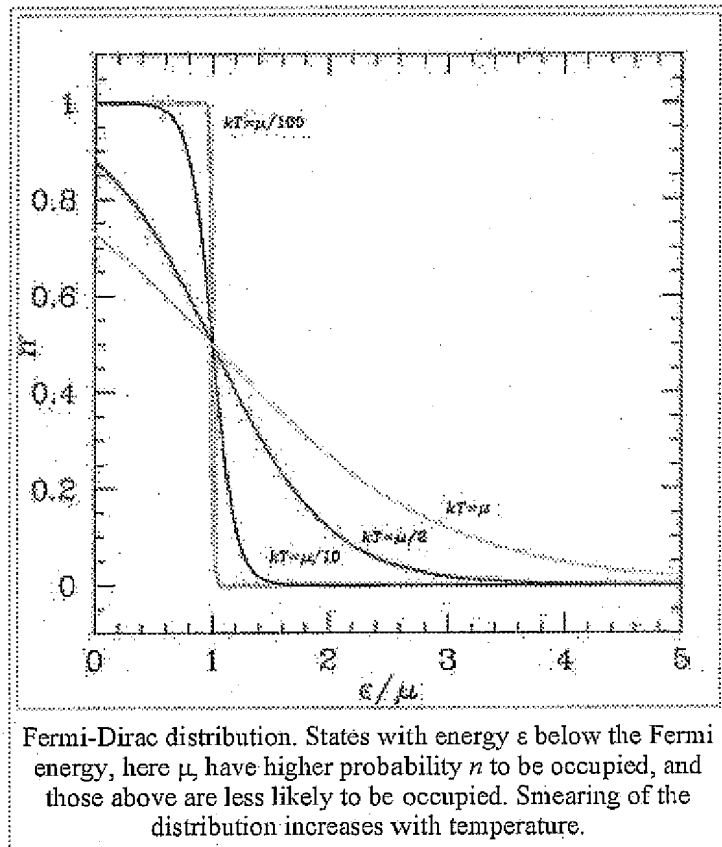
In the preceding description an important fact is ignored for the sake of simplicity: the *dispersion* of the energy. The reason that the energies of the states are broadened into a band is that the energy depends on the value of the wave vector, or *k-vector*, of the electron. The k-vector, in quantum mechanics, is the representation of the momentum of a particle.

The dispersion relationship determines the effective mass,  $m^*$ , of electrons or holes in the semiconductor, according to the formula:

$$m^* = \hbar^2 \cdot \left[ \frac{d^2 E(k)}{dk^2} \right]^{-1}$$

The effective mass is important as it affects many of the electrical properties of the semiconductor, such as the electron or hole mobility, which in turn influences the *diffusivity* of the charge carriers and the electrical conductivity of the semiconductor.

Typically the effective mass of electrons and holes are different. This affects the relative performance of *p-channel* and *n-channel* IGFETs, for example (Muller & Kamins 1986:427).



The top of the valence band and the bottom of the conduction band might not occur at that same value of  $k$ . Materials with this situation, such as silicon and germanium, are known as *indirect bandgap* materials. Materials in which the band extrema are aligned in  $k$ , for example gallium arsenide, are called *direct bandgap* semiconductors. Direct gap semiconductors are particularly important in optoelectronics because they are much more efficient as light emitters than indirect gap materials.

## Carrier generation and recombination

*For more details on this topic, see Carrier generation and recombination.*

When ionizing radiation strikes a semiconductor, it may excite an electron out of its energy level and consequently leave a hole. This process is known as *electron-hole pair generation*. Electron-hole pairs are constantly generated from thermal energy as well, in the absence of any external energy source.

Electron-hole pairs are also apt to recombine. Conservation of energy demands that these recombination events, in which an electron loses an amount of energy larger than the band gap, be accompanied by the emission of thermal energy (in the form of phonons) or radiation (in the form of photons).

In some states, the generation and recombination of electron-hole pairs are in equipoise. The number of electron-hole pairs in the steady state at a given temperature is determined by quantum statistical mechanics. The precise quantum mechanical mechanisms of generation and recombination are governed by conservation of energy and conservation of momentum.

As the probability that electrons and holes meet together is proportional to the product of their amounts, the product is in steady state nearly constant at a given temperature, providing that there is no significant electric field (which might "flush" carriers of both types, or move them from neighbour regions containing more of them to meet together) or externally driven pair generation. The product is a function of the temperature, as the probability of getting enough thermal energy to produce a pair increases with temperature, being approximately  $1 \times \exp(-E_G / kT)$ , where  $k$  is Boltzmann's constant,  $T$  is absolute temperature and  $E_G$  is band gap.

The probability of meeting is increased by carrier traps – impurities or dislocations which can trap an electron or hole and hold it until a pair is completed. Such carrier traps are sometimes purposely added to reduce the time needed to reach the steady state.

## Doping

*For more details on this topic, see Doping (semiconductor).*

The property of semiconductors that makes them most useful for constructing electronic devices is that their conductivity may easily be modified by introducing impurities into their crystal lattice. The process of adding controlled impurities to a semiconductor is known as *doping*. The amount of impurity, or dopant, added to an *intrinsic* (pure) semiconductor varies its level of conductivity. Doped semiconductors are often referred to as *extrinsic*. By adding impurity to pure semiconductors, the electrical conductivity may be varied not only by the number of impurity atoms but also, by the type of impurity atom and the changes may be thousand folds and million folds. For example -  $1 \text{ cm}^3$  of a metal or semiconductor specimen has a number of atoms of the order of  $10^{22}$ . Since every atom in metal

donates at least one free electron for conduction in metal,  $1 \text{ cm}^3$  of metal contains number of free electrons in the order of  $10^{22}$ . At the temperature close to  $20^\circ\text{C}$ ,  $1 \text{ cm}^3$  of pure germanium contains about  $4.2 \times 10^{22}$  atoms and  $2.5 \times 10^{13}$  free electrons and  $2.5 \times 10^{13}$  holes (empty spaces in crystal lattice having positive charge) The addition of 0.001% of arsenic (impurity) donates extra  $10^{17}$  free electrons in the same volume and the electrical conductivity increases about 10,000 times. "

## Dopants

The materials chosen as suitable dopants depend on the atomic properties of both the dopant and the material to be doped. In general, dopants that produce the desired controlled changes are classified as either electron acceptors or donors. A donor atom that activates (that is, becomes incorporated into the crystal lattice) donates weakly-bound valence electrons to the material, creating excess negative charge carriers. These weakly-bound electrons can move about in the crystal lattice relatively freely and can facilitate conduction in the presence of an electric field. (The donor atoms introduce some states under, but very close to the conduction band edge. Electrons at these states can be easily excited to conduction band, becoming free electrons, at room temperature.) Conversely, an activated acceptor produces a hole. Semiconductors doped with **donor** impurities are called *n-type*, while those doped with acceptor impurities are known as *p-type*. The n and p type designations indicate which charge carrier acts as the material's majority carrier. The opposite carrier is called the minority carrier, which exists due to thermal excitation at a much lower concentration compared to the majority carrier.

For example, the pure semiconductor silicon has four valence electrons. In silicon, the most common dopants are IUPAC group 13 (commonly known as *group III*) and group 15 (commonly known as *group V*) elements. Group 13 elements all contain three valence electrons, causing them to function as acceptors when used to dope silicon. Group 15 elements have five valence electrons, which allows them to act as a donor. Therefore, a silicon crystal doped with boron creates a p-type semiconductor whereas one doped with phosphorus results in an n-type material. for more details press on the blue buttons.

## Carrier concentration

The concentration of dopant introduced to an intrinsic semiconductor determines its concentration and indirectly affects many of its electrical properties. The most important factor that doping directly affects is the material's carrier concentration. In an intrinsic semiconductor under thermal equilibrium, the concentration of electrons and holes is equivalent. That is,

$$n = p = n_i$$

If we have a non-intrinsic semiconductor in thermal equilibrium the relation becomes:  $n_0 * p_0 = (n_i)^2$

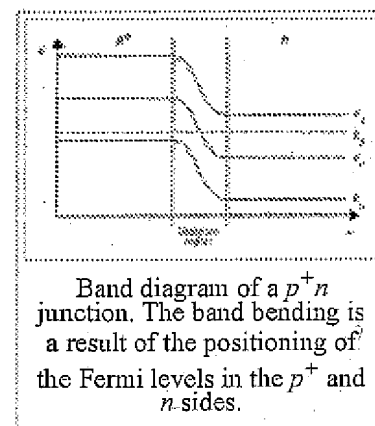
Where  $n$  is the concentration of conducting electrons,  $p$  is the electron hole concentration, and  $n_i$  is the material's intrinsic carrier concentration. Intrinsic carrier concentration varies between materials and is dependent on temperature. Silicon's  $n_i$ , for example, is roughly  $1.6 \times 10^{10} \text{ cm}^{-3}$  at 300 kelvin (room temperature).

In general, an increase in doping concentration affords an increase in conductivity due to the higher concentration of carriers available for conduction. Degenerately (very highly) doped semiconductors have conductivity levels comparable to metals and are often used in modern integrated circuits as a replacement for metal. Often superscript plus and minus symbols are used to denote relative doping

concentration in semiconductors. For example,  $n^+$  denotes an n-type semiconductor with a high, often degenerate, doping concentration. Similarly,  $p^-$  would indicate a very lightly doped p-type material. It is useful to note that even degenerate levels of doping imply low concentrations of impurities with respect to the base semiconductor. In crystalline intrinsic silicon, there are approximately  $5 \times 10^{22}$  atoms/cm<sup>3</sup>. Doping concentration for silicon semiconductors may range anywhere from  $10^{13}$  cm<sup>-3</sup> to  $10^{18}$  cm<sup>-3</sup>. Doping concentration above about  $10^{18}$  cm<sup>-3</sup> is considered degenerate at room temperature. Degenerately doped silicon contains a proportion of impurity to silicon in the order of parts per thousand. This proportion may be reduced to parts per billion in very lightly doped silicon. Typical concentration values fall somewhere in this range and are tailored to produce the desired properties in the device that the semiconductor is intended for.

## Effect on band structure

Doping a semiconductor crystal introduces allowed energy states within the band gap but very close to the energy band that corresponds with the dopant type. In other words, donor impurities create states near the conduction band while acceptors create states near the valence band. The gap between these energy states and the nearest energy band is usually referred to as dopant-site bonding energy or  $E_B$  and is relatively small. For example, the  $E_B$  for boron in silicon bulk is 0.045 eV, compared with silicon's band gap of about 1.12 eV. Because  $E_B$  is so small, it takes little energy to ionize the dopant atoms and create free carriers in the conduction or valence bands. Usually the thermal energy available at room temperature is sufficient to ionize most of the dopant.



Dopants also have the important effect of shifting the material's Fermi level towards the energy band that corresponds with the dopant with the greatest concentration. Since the Fermi level must remain constant in a system in thermodynamic equilibrium, stacking layers of materials with different properties leads to many useful electrical properties. For example, the p-n junction's properties are due to the energy band bending that happens as a result of lining up the Fermi levels in contacting regions of p-type and n-type material.

This effect is shown in a *band diagram*. The band diagram typically indicates the variation in the valence band and conduction band edges versus some spatial dimension, often denoted  $x$ . The Fermi energy is also usually indicated in the diagram. Sometimes the *intrinsic Fermi energy*,  $E_i$ , which is the Fermi level in the absence of doping, is shown. These diagrams are useful in explaining the operation of many kinds of semiconductor devices.

## Preparation of semiconductor materials

Semiconductors with predictable, reliable electronic properties are necessary for mass production. The level of chemical purity needed is extremely high because the presence of impurities even in very small proportions can have large effects on the properties of the material. A high degree of crystalline perfection is also required, since faults in crystal structure (such as dislocations, twins, and stacking faults) interfere with the semiconducting properties of the material. Crystalline faults are a major cause of defective semiconductor devices. The larger the crystal, the more difficult it is to achieve the

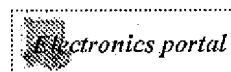
necessary perfection. Current mass production processes use crystal ingots between four and twelve inches (300 mm) in diameter which are grown as cylinders and sliced into wafers.

Because of the required level of chemical purity and the perfection of the crystal structure which are needed to make semiconductor devices, special methods have been developed to produce the initial semiconductor material. A technique for achieving high purity includes growing the crystal using the Czochralski process. An additional step that can be used to further increase purity is known as zone refining. In zone refining, part of a solid crystal is melted. The impurities tend to concentrate in the melted region, while the desired material recrystallizes leaving the solid material more pure and with fewer crystalline faults.

In manufacturing semiconductor devices involving heterojunctions between different semiconductor materials, the lattice constant, which is the length of the repeating element of the crystal structure, is important for determining the compatibility of materials.

## See also

- Effective mass
- Electronic band structure
- Bloch waves
- Tight-binding model
- Electron mobility
- Exciton
- Semiconductor device fabrication
- List of semiconductor materials
- Micro-Pulling-Down
- Semiconductor industry
- Quantum tunneling
- Semiconductor chip
- Semiconductor device
- Solid-state chemistry
- Spintronics
- Wide bandgap semiconductors



## References

- <sup>^</sup>. They are used in many applications like solar cells. International Union of Pure and Applied Chemistry. "semiconductor (<http://goldbook.iupac.org/S05591.html>)". *Compendium of Chemical Terminology* Internet edition.

## Notes

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## External links

- Howstuffworks' semiconductor page (<http://science.howstuffworks.com/diode.htm>)
- Semiconductor Concepts at Hyperphysics (<http://hyperphysics.phy-astr.gsu.edu/hbase/solids/semcn.html>)
- Semiconductor OneSource Hall of Fame (<http://www.semi1source.com/shof/>), Glossary (<http://www.semiconductorglossary.com/>)
- Principles of Semiconductor Devices (<http://ece-www.colorado.edu/~bart/book/book/>) by Bart Van Zeghbroeck, University of Colorado. An online textbook
- US Navy Electrical Engineering Training Series (<http://www.tpub.com/content/neets/14179/index.htm>)
- NSM-Archive (<http://www.ioffe.rssi.ru/SVA/NSM/Semicond/index.html>) Physical Properties of Semiconductors

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X. Related Proceedings Appendix

There are no decisions rendered by a court or the Board in any proceeding identified pursuant to 37C.F.R. § 41.37(c)(1)(ii).